Invisible Higgs Decay at the LHeC

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The possibility that the 125 GeV Higgs boson may decay into invisible non-standard-model (non-SM) particles is theoretically and phenomenologically intriguing. In this letter we investigate the sensitivity of the Large Hadron Electron Collider (LHeC) to an invisibly decaying Higgs, in its proposed high luminosity running mode. We focus on the neutral current Higgs production channel which offers more kinematical handles than its charged current counterpart. The signal contains one electron, one jet and large missing energy. With a cut-based parton level analysis, we estimate that if the hZZ coupling is at its standard model (SM) value, then assuming an integrated luminosity of $1\,\mathrm{ab}^{-1}$ the LHeC with the proposed 60 GeV electron beam (with -0.9 polarization) and 7 TeV proton beam is capable of probing $\mathrm{Br}(h \to \not{E}_T) = 6\%$ at 2σ level. Good lepton veto performance (especially hadronic τ veto) in the forward region is crucial to the suppression of the dominant Wje background. We also explicitly point out the important role that may be played by the LHeC in probing a wide class of exotic Higgs decay processes and emphasize the general function of lepton-hadron colliders in precision study of new resonances after their discovery in hadron-hadron collisions.

I. INTRODUCTION

After the discovery of the 125 GeV Higgs boson [1, 2], naturally the next step is measuring its properties as accurately as possible, which tests the standard model (SM) in its most elusive sector and may hopefully reveal its connection to physics beyond the standard model (BSM). So far, determination of the Higgs boson spin and parity and measurements of the Higgs signal strength in various production and decay channels have been carried out, all of which turned out to be consistent with SM predictions. It is worth noting that besides the decay modes which have promising observability in SM, attention has also been paid to interesting rare (such as flavor-changing [3, 4]) or exotic [5] decay modes which is predicted to be negligibly small in SM. These modes may easily get enhanced in various BSM theories, and with the potential large number of Higgs bosons expected to be produced at the LHC and future colliders, may even surprise us with a spectacular discovery [5].

One of the most interesting exotic Higgs decay channel is Higgs decaying into invisible (or undetectable) non-SM particles [6, 7]. Already long before the Higgs boson discovery, search of this mode has drawn a lot of attention [8–13]. Near and after the Higgs boson discovery, constraints has been put on the invisible Higgs decay branching fraction via both Higgs signal strength measurements and direct searches. The most stringent limit from direct search now comes from the ATLAS search for an invisibly decaying Higgs in the vector boson fusion (VBF) channel [14], which constrains the Higgs invisible branching fraction to be less than 29% at 95% confidence level. The importance of this exotic Higgs decay channel however cannot be overemphasized because it may shed light on the link between Higgs boson and the dark matter (DM), whose existence has been established via its gravitational effects. It is tempting to speculate about their connection since there is no evidence of DM interacting non-gravitationally with other SM particles which have been found for a long time and also the Higgs is one of the only few portals by which SM particles are able to interact with singlet hidden sector matter via (super-)renormalizable Lagrangians. Indeed the situation that the Higgs (or the Higgs sector) interacting with DM (or a dark sector) occurs in many extensions of the SM, for example in models which aim to solve the hierarchy problem, such as supersymmetry (SUSY) [15–19], composite Higgs [20], extra dimensions [21], Little Higgs [22], Twin Higgs [23, 24], in simple dark matter models [25–27], and in Higgs portal models [28–34]. If the dark matter (or dark sector) particle is sufficiently light, then the invisible Higgs decay thereof can naturally reach a detectable branching fraction. Invisible Higgs decay is also an important signature of some majoron and neutrino mass models [35–39]. In fact the collider search for invisible Higgs decay has become and will remain an important constraint on wide classes of BSM scenarios. It is thus highly motivated to investigate all sensitive search strategies within the possibly available accelerator and detector designs.

At the LHC, it has been recognized that the VBF and ZH associated production channels will provide the most sensitive probe on an invisibly decaying Higgs in the long run [40–43]. At lepton colliders such as the International Linear Collider (ILC), Future Circular Collider (FCC-

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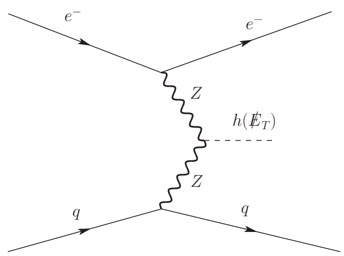

FIG. 1: Feynman diagram of the NC production of an invisible Higgs at the LHeC.

ee) or the Circular Electron Positron Collider (CEPC), sensitivity to $\mathrm{Br}(h \to \not{E}_T) < 1\%$ can easily be gained due to the much cleaner collider environment and the availability of mass recoil methods [44, 45]. However it is still helpful to investigate whether other options exist and may help to provide useful information on our understanding of physics behind the scene.

In this letter, we investigate the possibility of utilizing the Large Hadron Electron Collider (LHeC) [46] with its recently proposed and discussed high luminosity run [47–49] to probe an invisibly decaying Higgs. The LHeC plans to collide a 60 GeV electron beam with the 7 TeV proton beam in the LHC ring and is designed to run synchronously with the High Luminosity Large Hadron Collider (HL-LHC). It was originally designed to deliver an integrated luminosity of 100 fb^{-1}. With the potential role of the LHeC in precision Higgs physics being noticed, recently there has been proposals and discussion on the collider's luminosity upgrade which is designed to deliver an integrated luminosity of up to 1 ab^{-1} [47–49]. With such conditions the LHeC indeed becomes a Higgs boson factory and will offer exciting opportunities in precision Higgs studies, especially with respect to exotic Higgs decays. We note that there has been quite a few studies on Higgs boson physics at the LHeC [50–58]. The possibility of using the LHeC to study BSM Higgs decays has been mentioned in [49].

At the LHeC the Higgs boson is produced via two major channels: charged current (CC) and neutral current (NC). In CC production, the Higgs is produced via WW fusion and has a larger cross section. However, when searching for an invisible Higgs, WW fusion production results in mono-jet plus missing energy, which accidentally coincides with the CC deeply inelastic scattering (DIS) background. Moreover, the lack of kinematic handles in the final state renders this signal channel even more difficult to distinguish from its major background. Therefore in this letter we focus on NC production which results in one electron, one jet and large missing energy in the final state (see FIG. 1 for its Feynman diagram). In the next section we present a cut-based parton level analysis of the relevant signal and backgrounds and derive an estimation on the LHeC sensitivity to invisible Higgs decay branching fraction with its high luminosity mode. The main conclusion is that the LHeC in its high luminosity mode has the potential to probe $\mathrm{Br}(h \to \not{E}_T) = 6\%$ at 2σ level (assuming a SM hZZ coupling), when only statistical uncertainty is taken into account. We will also discuss about crucial assumptions made in our analysis and comment on possible future improvement and promising potential of lepton-hadron colliders in precision studies of new resonances (including the study of various exotic Higgs decays) in the last section before we conclude the letter. We emphasize that an electron-proton collider with even higher beam energies (*e.g.* $E_e = 120$ GeV$, E_p = 50$ TeV) may has better sensitivity to the invisible Higgs decay (and other exotic Higgs decays), which is interesting and worth pursuing in its own right but beyond the scope of this letter.

II. COLLIDER SENSITIVITY

A. Signal and Backgrounds

We take Higgs production at the LHeC through ZZ fusion as our signal process. Its cross section depends on the hZZ coupling in the model considered. We use κ_Z to denote the hZZ coupling strength relative to its SM value. Then we define

$$C^2_{\mathrm{MET}} = \kappa^2_Z \times \mathrm{Br}(h \to \not{E}_T) \tag{1}$$

with which we are able to present the sensitivity results conveniently. The SM process $h \to ZZ^* \to 4\nu$ has an extremely small branching ratio and will neither be included in the signal nor backgrounds.

The main irreducible backgrounds include

$$p + e^- \to W^- + j + \nu_e, (Wj\nu) \tag{2}$$
$$p + e^- \to Z + j + e^-, (Zje) \tag{3}$$

which result in one electron, one jet and missing transverse energy via $W \to e\nu$ and $Z \to \nu\nu$ respectively. Photoproduction of $W + j$ is also an irreducible background if the W boson decays to an electron. Although its cross section is initially very large, it is found to be negligible after all selection cuts described below, due to its distinct kinematic features. We do not expect the $W + j$ production via resolved photons contributes sizably to the total background because we require large missing energy in the event which should boost the W boson to the kinematic regime where the resolved photon contribution is expected to be small [59].

We note that these irreducible backgrounds do not contain strong coupling at leading order, which is different from the VBF search for an invisible Higgs encountered at the LHC. At the LHC, the VBF search of an invisible Higgs boson has important $Vjj(V = W, Z)$ backgrounds which contain the process of QCD dijet production with a weak boson radiated from one of the

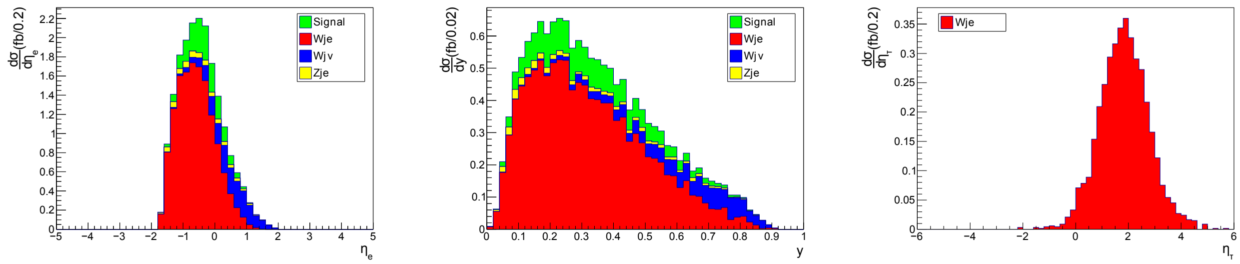

FIG. 2: Left: η_e distribution of the signal and major backgrounds just before the η_e cut. Middle: y distribution of the signal and major backgrounds just before the y cut. Right: τ lepton pseudorapidity distribution of the $Wje(W \to \tau\nu)$ background just before the lepton veto.

quark line. However at the LHeC the corresponding process is of purely electroweak nature which is one of the attractive features of a lepton-hadron collider machine.

There are also reducible backgrounds which come from a variety of sources. Anti-top production in which $\bar{t}$ decays to $\bar{b} + e^- + \bar{\nu}_e$ constitutes a background because b anti-tagging cannot be expected to be fully efficient. However this background also turns out to be negligible after all selection cuts below. A threatening reducible background is

$$p + e^- \to W^\pm + j + e^-, (Wje) \tag{4}$$

in which the W boson decays to $l\nu\,(l = e, \mu, \tau)$ and the charged lepton (e, μ, τ) from W decay falls out of detector acceptance or fails to be reconstructed and identified. In fact this background turns out to be dominant after all selection cuts.

e + multijet production is a reducible background in which missing energy comes from jet energy mismeasurement. We do not simulate this background but its contribution is expected to be negligible after several demanding cuts required in the analysis, especially $\not{E}_T > 70$ GeV and the missing energy isolation cut $I \equiv \Delta\phi_{\not{E}_T, j} > 1\,\text{rad}$. One further reducible background is CC $jj\nu$ production in which one jet is misidentified as an electron. In the following we simply assume a competent detector performance and drop this background from the analysis.

B. Analysis and Results

We generate the signal and background samples at leading order with MadGraph5_aMC@NLO [60]. The collider parameters are taken to be $E_e = 60$ GeV, $E_p = 7$ TeV with the electron beam being -0.9 polarized, i.e. 90% left-handed. These parameter choices including polarization are in accordance with the LHeC Higgs factory parameters presented in [47]. The Higgs boson mass is taken to be 125 GeV. The parton distribution function used is NNPDF2.3 at leading order [61]. We take the renormalization and factorization scale to be the Z boson mass. For all the signal and background considered, K-factors are taken to be 1 [62–64]. We perform a parton level analysis with detector resolution taken into account by the jet and lepton energy resolution formula $\frac{\sigma_E}{E} = \frac{\alpha}{\sqrt{E}} \oplus \beta$ where for jet energy smearing $\alpha = 0.6\ \text{GeV}^{1/2}, \beta = 0.03$ and for lepton energy smearing $\alpha = 0.05\ \text{GeV}^{1/2}, \beta = 0.0055$. Event analysis is performed with the help of MadAnalysis 5 [65]. Whenever needed, the expected statistical significance Z is calculated according to the formula $Z = \sqrt{2((S+B)\ln(1+S/B) - S)}$ [66] where S and B denote the expected signal and background event number, respectively.

As to signal and background analysis, we require at least one electron and at least one jet in the final state. All the signal and background samples are required to pass the following basic cuts:

$$\begin{aligned} &p_{Tj} > 20\ \text{GeV}, |\eta_j| < 5.0, \\ &p_{Tl} > 20\ \text{GeV}, |\eta_l| < 5.0, \Delta R_{jl} > 0.4 \end{aligned} \tag{5}$$

Then we impose the following sequence of selection cuts to further discriminate between signal and background:

1. $\not{E}_T > 70$ GeV.

2. Missing energy isolation: $I > 1\,\text{rad}$.

3. Pseudorapidity gap of the jet and the electron satisfies $\eta_j - \eta_e > 3.0$.

4. The azimuthal angle difference of the electron and the jet satisfies $\Delta\phi_{ej} \equiv |\phi_j - \phi_e| < 1.2$.

5. The pseudorapidity of the electron satisfies $\eta_e \in [-1.2, 0.6]$.

6. Inelasticity cut: the inelasticity variable y is defined as $y = \frac{p_1 \cdot (k_1 - k_2)}{p_1 \cdot k_1}$, where p_1 is the 4-momenta of the initial proton, k_1 is the 4-momenta of the initial electron, k_2 is the 4-momenta of the out-going electron. Then we require $y \in [0.06, 0.5]$.

7. Lepton veto: additional electron, muon or tagged hadronic τ are vetoed. (See text for detail.)

Cross Section (fb)	Basic Cuts	$\not{E}_T > 70$ GeV	$I > 1$	$\eta_j - \eta_e > 3.0$	$\Delta\phi_{ej} < 1.2$	$\eta_e \in [-1.2, 0.6]$	$y \in [0.06, 0.5]$	Lepton Veto
Signal ($C^2_{\rm MET} = 1$)	16.1	8.80	8.23	4.68	2.37	2.16	1.77	1.77
Wje	816	158	143	51.7	13.9	11.3	9.13	1.96
$Wj\nu$	192	102	101	5.68	2.36	1.33	0.387	0.387
Zje	42.7	13.8	12.1	1.64	0.683	0.464	0.326	0.326

TABLE I: The cross section (in unit of fb) of the signal and major backgrounds after application of each cut in the corresponding column. Other backgrounds contribute less than 0.1 fb in total after all cuts and are not displayed in the table.

We assume additional electrons satisfying $p_T > 7$ GeV and $|\eta| < 5.0$ and muons satisfying $p_T > 5$ GeV and $|\eta| < 5.0$ can all be vetoed. As to the τ decay, we adopt the collinear approximation in which we simply assume on average the visible electron or muon from τ decay carries 1/3 of the parent τ momentum and the visible part of a hadronically decaying τ carries 1/2 of the parent τ momentum. We consider a 70% tagging efficiency [67] for a hadronically decaying τ for the veto purpose, if the τ lepton satisfies $p_{T,\tau_{\text{had-vis}}} > 20$ GeV and $|\eta| < 5.0$ ($p_{T,\tau_{\text{had-vis}}}$ denotes the transverse momentum of the visible part of the hadronically decaying τ). We note that we have allowed the lepton veto capability to extend to $|\eta_{\max}| = 5.0$, in contrast to the commonly assumed $|\eta_{\max}| = 2.5$ assumed in the usual LHC analysis. This is due to the expected very large pseudorapidity coverage of the LHeC tracking detector and muon detector [46, 68].

In the sequence of cuts listed above, $\not{E}_T > 70$ GeV and the missing energy isolation requirement will significantly suppress the $e+$ multijet background. When calculating the missing energy the electron and hadronic τ which satisfy $|\eta| < 5.0$ but fail to be identified are counted in the p_T balance while muons which fail to be identified are always excluded in the p_T balance. The pseudorapidity gap requirement, azimuthal angle difference cut are analogous to $|\eta_{j_1} - \eta_{j_2}|$ and ϕ_{jj} cuts employed in the LHC VBF search for an invisible Higgs boson [10]. They are very effective in reducing all three major backgrounds. Then we try simple kinematic variables like the electron pseudorapidity η_e and inelasticity y to further enhance the statistical significance. To motivate those cuts beyond the counterparts of the usual ones employed in the VBF search for an invisible Higgs at the LHC, we plot the η_e, y distribution of the signal and major backgrounds in FIG. 2 (left and middle) just before applying the correspongding cuts. The signal and background cross sections after each cut are listed in Table I, in which the signal cross section is calculated assuming $C^2_{\rm MET} = 1$. We note that if we target $C^2_{\rm MET} = 0.06$, we will get an expected signal cross section of 0.106fb and total background cross section 2.761fb (we have included here about 0.1 fb contribution from other minor backgrounds), thus $S/B \approx 3.8\%$, and with an integrated luminosity of 1 ab^{-1} the expected statistical significance will reach $Z = 2.00$. We also plot the significance contour for a targeted range of $C^2_{\rm MET}$ and the luminosity parameter in FIG. 3.

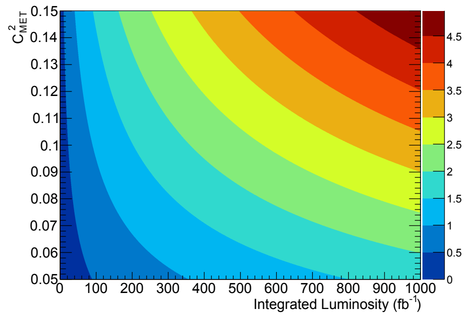

FIG. 3: The expected significance contour for an invisible Higgs at the LHeC. The colors indicate the value of the expected statistical significance with the correspondence displayed by the scale on the right.

III. DISCUSSION AND CONCLUSION

In this letter we have studied at the parton level the possibility of using the LHeC to search for an invisibly decaying Higgs boson and find that the LHeC has promising potential to discover or constrain this important exotic Higgs decay mode. The η_e cut and the inelasticity cut are found to be very effective in suppressing the $Wj\nu$ background which has no counterpart in the VBF search for an invisible Higgs at the LHC. After all selection cuts the largest background turns out to be the Wje process in which the charged leton (especially τ) from W boson decay fails to be identified. In fact this Wje process finally constitutes about 70% of the total background. We take advantage of the expected large acceptance of the LHeC tracking detector and muon detector, with which the lepton veto is able to remove nearly 80% of the Wje background. Especially we find that the lepton veto capability in the forward region $\eta \in [2.5, 4.0]$ is essential. To illustrate this point we plot the pseudorapidity distribution of the τ lepton from the W boson decay in the Wje background (FIG. 2 (right)). Due to lepton universality this also represents the pseudorapidity distribution of the electron/muon from W boson decay in the Wje background. From the plot it is clear that the charged lepton from W boson decay in Wje background are mostly distributed in $\eta \in [0.0, 4.0]$ and large portions of events still reside in $\eta \in [2.5, 4.0]$. If the lepton veto is only possible in $\eta \in [-2.5, 2.5]$, the total background

will nearly double. It is thus highly recommended that a good lepton veto capability should be maintained in the forward region $\eta \in [2.5, 4.0]$.

The sensitivity of the LHeC to an invisibly decaying Higgs boson could be further enhanced via a multivariate analysis, which is worth pursuing [69] but beyond the scope of the present paper. Compared with the concurrent search at the HL-LHC, the invisible Higgs search at the LHeC has the further advantage of not suffering from pile-up, a crucial factor of which is commonly not taken account sufficiently in the LHC analysis. Of course both searches are worth exploiting and being combined to produce the best sensitivity to the invisible Higgs decay with the available LHC infrastructure. Even if an excess of VBF dijet+$\not{E}_T$ events is first observed at the HL-LHC, signals from additional channels are still required to pin down the origin of the $\not{E}_T$ signature. The LHeC search for an invisible Higgs may play an important role in this process.

Our study clearly justifies a luminosity upgrade to 1 ab^{-1} for the LHeC to become a Higgs boson factory [47] and demonstrates its huge potential on study of exotic Higgs decays. Besides the invisible Higgs decay, the LHeC is suited to the study of those exotic Higgs decays which suffer from large backgrounds, trigger or p_T threshold problem at the (HL-)LHC such as $h \to 4b$, $h \to 2b2\tau$, $h \to 4j$, $h \to b\bar{b} + \not{E}_T$ [70], $h \to \gamma + \not{E}_T$, $h \to Z + \not{E}_T$ [71]. Work on these directions is in progress [72]. The demonstration of the LHeC potential on studying exotic Higgs decays reveals an important aspect of lepton-hadron colliders with respect to precision study after the discovery of a new resonance in hadron-hadron collisions, which has not been unexpected since the early study of measuring the bottom Yukawa coupling at the LHeC [50]. Although usually the ideal precision measurement should finally be achieved at a lepton collider, this most precise measurement can only be reached with sufficient center-of-mass energy available. Without the help of such a lepton collider then the best use of a hadron beam can be made via colliding it against a lepton beam to make foreseeable precision studies, which may even unravel exciting deviations from the SM within the shortest time.

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